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ABSTRACT

The various tasks that have to be undertaken before the construction of a new school can begin are complex. In Great Britain, the Local Government Operational Research Unit was asked by Northumberland County Council to examine how delays in the preconstruction period might be reduced. A detailed analysis was made of nine school building projects on which construction had been scheduled to begin in the 1964/65 program. The results of the study showed that by using critical path analysis--a technique developed in the early days of operational research--the time between receipt of the central department's approval for a new school and the signing of the building contract could have been reduced by at least 10 percent. This report describes the main features of the technique and shows how it can be used to control the early stages of school building projects. (Author/MLF)

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Application of Critical Path Analysis to Design and Administrative Procedures

SUSAN BRAUN and KENNETH N. GROOM

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Application of Critical Path Analysis to Design and Administrative Procedures

SUSAN BRAUN and KENNETH N. GROOM

November 1969
Report No. S.11

This report describes work that the Local Government Operational Research Unit has carried out into the application of critical path analysis to administrative processes. The study was made possible by Northumberland County Council, whose support is gratefully acknowledged, and the other member authorities of the Unit. A full list of members is given at the end of the report.

This report is issued free of charge to member authorities; the price to non-members is 10s. (50p).

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The Unit was established on 1 April 1965. Its aims are (i) to undertake studies by operational research methods to assist local authorities in their policy and management decisions, and (ii) to assist local authorities who wish to apply the results of these studies. Membership is open to all the major local authorities in the United Kingdom. Annual subscriptions range from £200 to £800, on a scale based on rateable value.

The Unit is part of the Royal Institute of Public Administration and is the responsibility for administrative purposes of the Institute's Executive Council. The Executive Council has appointed a Board to determine the principles on which the research programme should be developed, and to advise it on matters relating to the administration of the Unit, including its finances. The members of the Board are representative of the authorities supporting the Unit.

The various tasks that have to be undertaken before the construction of a new school can begin—from acquiring a suitable site to agreeing the school's design and negotiating the building contract—are complex. They involve several departments of a local authority as well as the Department of Education and Science. These procedures sometimes become so protracted that construction cannot begin in time for the school to be completed by the required date. In consequence, the children who would have attended the new school have to be transported to other schools, causing inconvenience and extra expense to the local education authority.

The Local Government Operational Research Unit was asked by Northumberland County Council to examine how delays in the pre-construction period might be reduced. The study that was carried out will be of interest to other local authorities faced with the problem of speeding up complex administrative procedures in both education and other services. Since the study was completed, the system of administering the school building programme has been modified to that of the rolling programme. However, the introduction of the new system, described in DES circular 13/68, does not affect the usefulness of the study which this report describes.

A detailed analysis was made of nine school-building projects on which construction had been scheduled to begin in the 1964/65 programme. The results of the study showed that by using critical path analysis—a technique developed in the early days of operational research—the time between receipt of the central department's approval for a new school and the signing of the building contract could have been reduced by at least 10 per cent.

The critical path method has, of course, long been known to local authorities and used by them in the planning and control of construction and design work. Much less use has been made, however, of this method in the field of administration. This report describes the main features of the technique and shows how it can be used to control the early stages of school building projects.

Outline of the Method

To apply critical path analysis, a project has to be broken down into its component steps, or *activities*. Then the logical sequence in which the activities should be carried out and the inter-relationships between them have to be established. This information is represented in graphical form on a network. In the second stage, the time required to complete each of these different activities is estimated and used to prepare a working schedule. Once this has been done it is possible to calculate the minimum total duration of the project and, in addition, to identify the critical activities—that is, those activities which, if delayed, will disrupt the entire project.

The network that has been prepared is used to control and co-ordinate the progress of the work in two ways. First, it can indicate when two or more activities which are not dependent on one another can be carried out at the same time. Second, the effect on the estimated completion date of unforeseen delays that may arise can be calculated, and corrective action taken. Alternative courses of action

can be quickly and easily tested by preparing alternative networks before a final decision is made.

Preparing the Network

Preliminary investigation showed that the preconstruction stages of a school building project can conveniently be divided into two main parts. The first concerns the acquisition of a suitable site for the new school. The second covers all the other tasks which must precede the signing of the building contract. A separate network was drawn for each set of activities using information on the projects completed in 1964/65.

The first step was to compile a list of all the major activities that might possibly, although not necessarily, occur in the course of a project. The list of site acquisition activities is shown in Table 1 and the list of design and administrative activities in Table 2. To keep the diagrams clear a short code name has been given to each activity. The code names are given in Tables 1 and 2. The code name of each site acquisition activity is ended with '.S' and each design and administrative activity with '.D'. Two types of activity were taken into account: those which indicate a

ACTIVITY NAME	Activity Code Name
Selection of a suitable site	A.S
Identification of the owner of the site	B.S
Preparation of a location plan of the site	C.S
Consideration of the suitability of the site	D.S
Determination of site boundaries	E.S
Obtaining permission to survey the site	F.S
Surveying of the site	G.S
Preparation of plans for site acquisition	H.S
Collection of information on public services	I.S
Waiting for owner to agree or be free to sell or lease the site	J.S
Site purchase negotiations	K.S
Notice of intent to seek planning permission for the site	L.S
Consideration of planning permission application for the site	M.S
Completion of District Valuer's questionnaire by District Authority	N.S
Preparation of the District Valuer's report	O.S
Await the Education Committee's approval of the prices and vendors fees	P.S
Preparation of the Mineral Valuer's report	Q.S
Await the Council's authorization of the loan application for the site	R.S
Consideration of loan sanction for the site by DES	S.S
Preparation of plans for conveyance	T.S
Completion of conveyance	U.S

TABLE 1: SITE ACQUISITION ACTIVITIES

ACTIVITY NAME	Activity Code Name
Consideration of inclusion of the project in the year's building programme by DES	A.D
Appointment of a Private Architect	B.D
Preparation of brief by Education Department	C.D
Consideration of brief by Architect	D.D
Preparation of satisfactory sketch plans	E.D
Consideration of the sketch plans by DES	F.D
Preparation of satisfactory final plans	G.D
Consideration of the final plans by DES	H.D
Await the Education Committee approval of the cost of the building	I.D
Await the County Council authorization of the loan application for the building	J.D
Consideration of loan sanction for the building before receiving the Council's authorization of the loan, by DES	K.D
The DES consideration of loan sanction for the building, after receiving the Council's authorization of the loan by DES	L.D
Consideration of planning permission application for the building	M.D
Period for reply to tender documents	N.D
Period for the submission of a priced Bill	O.D
Preparation of reductions to the tender	P.D
Preparation of SB 27	Q.D
Revision of plans in order to effect reductions	R.D
Revision of SB 16	S.D
Consideration of SB 27 plus any revision of plans and SB 16 necessary to effect reductions by DES	T.D
Signing of the Contract	U.D

TABLE 2: DESIGN AND ADMINISTRATIVE ACTIVITIES

specific job to be done, such as the preparation of sketch plans (activity E.D); and those which refer to a necessary waiting period, such as the time allocated for replies to an invitation to tender for the building contract (N.D). So far as critical path analysis is concerned, both these activities involve the use of time and are therefore treated in the same way.

Once the activity list had been prepared, it was necessary to define clearly the relationships between the different activities, so that the logical sequence in which they should be tackled could be determined. In some cases the relationships were obvious. The activity which refers to carrying out a survey of the proposed site (G.S), for example, clearly could not take place until permission to do so (F.S) had been granted. In other cases, however, the relationships were not so readily apparent. In these circumstances it was necessary to consult with the officers responsible for the particular activity in order to determine the correct interaction.

Care was taken to ensure that the relationships that were defined described a sequence of activities which would not give rise to work which might be wasted.

Work on the preparation of tender documents, for example, could be started before the Department of Education and Science had approved the final plans, but only at the risk of wasted time and effort if in the event this approval were not given. It may, of course, occasionally be necessary to take such a risk, and examples of when this might profitably be done are discussed in a later section. Ordinarily, however, the relationship between activities of this type should be treated as one of strict dependence. It is on this basis that the list of relationships shown in Tables 3 and 4 was prepared. As soon as the various activities and the relationships between them had been defined it was possible to prepare the networks. Certain symbols have come to be conventionally used in critical path analysis. These are as follows:

An *activity* which is a job to be done or a period of time which has to pass, is represented by an arrow to indicate the direction of the passage of time.

An *event*, or node, which is the point at which one activity ends and another begins, is represented by a circle.

A *dummy activity*, which is used as described below to preserve the logic of the network, is represented by a broken arrow.

Activity Codes (see Table 1 for Activity Names)	All the Activities which must Immediately Precede the Activity in the Left Hand Column
A.S	
C.S	A.S
E.S	A.S
D.S	C.S
F.S	D.S
Q.S	D.S
N.S	D.S
I.S	D.S
M.S	L.S
F.S	B.S
J.S	B.S
G.S	F.S
H.S	G.S
K.S	J.S, H.S, Q.S, N.S, I.S, M.S
T.S	J.S, H.S, Q.S, N.S, I.S, M.S
O.S	E.S, K.S
P.S	O.S
R.S	P.S
S.S	R.S
U.S	S.S, T.S

TABLE 3: RELATIONSHIPS BETWEEN SITE ACQUISITION ACTIVITIES

Activity Codes (see Table 2 for Activity Names)	All the Activities which must Immediately Precede the Activity in the Left Hand Column
A.D	
B.D	A.D
C.D	A.D
D.D	B.D, C.D
E.D	D.D
F.D	E.D
G.D	F.D
H.D	G.D
I.D	G.D
J.D	I.D.
K.D	G.D
L.D	K.D, J.D
M.D	G.D
N.D	H.D, L.D
O.D	N.D
P.D	O.D
Q.D	P.D
R.D	P.D
S.D	P.D
T.D	Q.D, S.D, R.D
U.D	T.D, M.D

TABLE 4: RELATIONSHIPS BETWEEN DESIGN AND ADMINISTRATIVE ACTIVITIES

It is often necessary to show that a particular activity cannot start until the completion of another activity, which is not adjacent to it in the network. The relationship between these two activities is conventionally shown by a broken arrow—known in critical path analysis as a 'dummy activity'. A dummy activity indicates that the later of the two activities is dependent on the completion of the first, but requires no time to be allocated to it. Dummy activities are also used to avoid confusion when two or more activities that could be carried out simultaneously occur between the same two events.

Examples of how dummy activities are used in practice can be seen in Figures 1 and 2. These show in simplified form the networks that were prepared for both sets of activities in school building projects. (We have not shown any interaction between the networks—although clearly they do interact.) The figures also show the conventional system of numbering events, whereby each event has a number that is higher than those events that precede it and lower than those which follow it.

Timing of Activities

To be an effective tool for the control of a project, the network must show not only the sequence of activities but the time that each activity is likely to take. Estimates

Figure 1. Network Diagram for the Acquisition of a School Site.

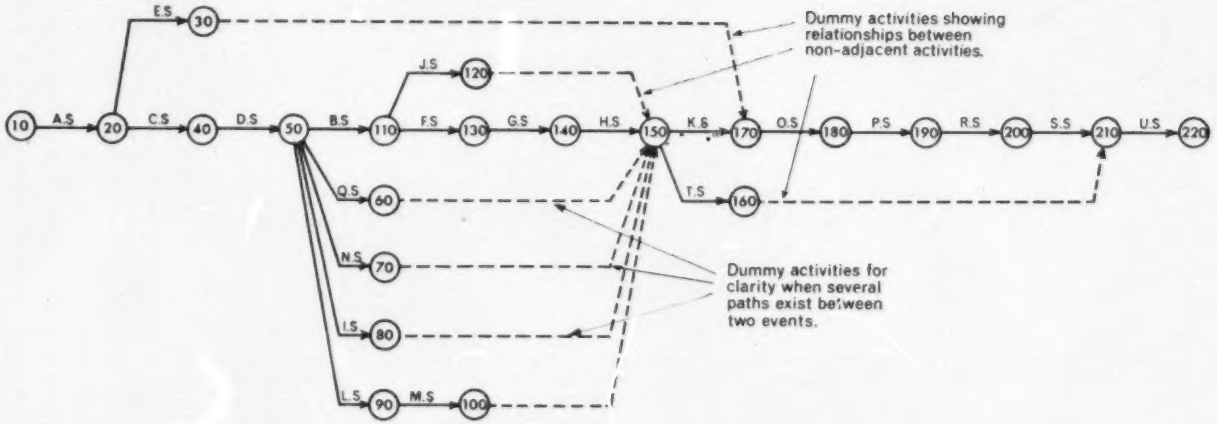
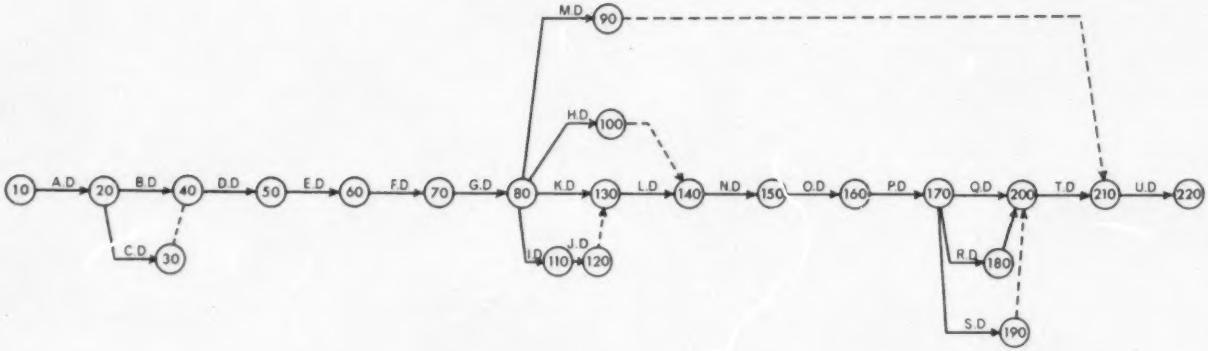


Figure 2 Network Diagram for the Design and Administrative Processes Preceding the signing of the Building Contract



of these times can be obtained by reference to past records, or from consultation with the officers familiar with the work to be done, or by a combination of the two.

From past data it is possible to find out how long each different activity has taken to complete in previous years. In some cases, such as the activity 'consider granting planning permission', the durations varied very little from project to project. It would be possible, therefore, to make a reasonable estimate of the future duration of activities of this type on the basis of their average duration in the past. In other cases, however, the time for completion varied considerably according to the type of project being considered—for example, whether the school in question was a secondary or primary school. For activities of this type, estimates of the time needed to complete them would have to be made by the officers concerned on the basis of their experience of the work in the past. The latter, in fact, is probably the most effective method of estimating activity durations in the initial stages of introducing critical path control. Once the system has been established, however, the routine recording of the information it requires will generate a continuous supply of data which can be used in preparing future networks.

A particular problem that has to be considered in relation to the school building programme is that of the amount of work which the County Architect's own staff could undertake at any one time. If more work is accepted than can be handled by the available staff then disruption of the working schedule and serious delays to one or more projects will result.

Analysis of the Network

Once the duration of the activities had been estimated the next step was to identify which of these activities were critical—that is, those activities that could not be delayed without delaying the whole project. Identification of the critical activities is central to the system of critical path analysis. By determining the critical activities the total time required to complete the work in the network can be established, and a working schedule produced that will be used to control the progress of the project.

The process by which the critical activities are found is as follows. First, using the estimated durations of each activity, a calculation is made of the earliest time at which each event could be reached. Second, by a reverse process, the latest time at which each event could be reached without increasing the total length of the project is also calculated. Those events for which the earliest event time and the latest event time are the same, mark the beginning and end of critical activities, and the route they trace through the network is the critical path. A more detailed description of the steps involved in the calculation of event times is given in the Appendix.

There were variations between the projects which were analysed in Northumberland but, in general, the same activities were found to be critical in most cases. They were of two kinds:

(a) Those that were critical because no other activities which might have provided some slack were in hand at the same time. Jobs which fell into this category included:

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Selection of a suitable site	(A.S)
Completion of conveyance	(U.S)
Consideration of brief	(D.D)
Preparation of sketch and final plans	(E.D & G.D)

(b) Those which required longer to complete than any other activities taking place between the same events. Activities of this type included:

Preparation of District Valuer's report where necessary	(O.S)
Preparation of Architect's brief	(C.D)
Period for reply to tender documents	(N.D)

Inspection of the networks in Figures 1 and 2 will show how these two types of critical activity come about.

It follows that there will be many activities which are not critical, but which have a (varying) amount of spare time, or 'float', associated with them. The float can be calculated by using the earliest and latest event time. The difference between the two times will represent the number of days by which the activity preceding the event might be delayed without having any serious effect on the duration of the project as a whole. Activities in Northumberland which were consistently found to be non-critical included considering granting planning permission for both the building and the site (M.D and M.S), and preparing plans for the conveyance of the site (T.S).

Attention is, naturally enough, concentrated during the course of the project on the critical activities. It is also important, however, to keep a constant control of non-critical activities to ensure that they do not in fact fall behind schedule and themselves become critical. Careful use of the float should enable management to schedule the work in such a way that the most efficient and economic use is made of the available staff and resources.

Having established the critical path and found which activities are critical and which are not, the networks are ready to be used to evaluate and control the projects they describe.

Evaluation of Completion Date

The first stage is to consider whether the estimated completion date—that is, the earliest event time of the end event—is acceptable. If, as is the case with the school building programme, the starting date is outside the control of the local authority, then the time needed to complete the necessary procedures may well exceed the time available. In this case a number of alternative courses of action are open to management in order to bring this date forward. Each possibility can be tested by reference to the network.

The straightforward way of reducing the total time needed to complete the work would be to assign extra staff to the critical activities, thus shortening the critical path and bringing forward the completion date. This might be done by transferring suitable staff from other duties to the project or, more reasonably, by utilizing the

float on non-critical activities to release staff for work on activities taking place at the same time that are critical. Careful analysis of the network will show where this kind of adjustment might most profitably be made. Care must be taken, however, that in doing so, non-critical activities are not themselves made critical.

If, when these possibilities have been considered and the new networks drawn, the completion date is still unacceptable, then the only option remaining to management is to take a calculated risk by ignoring one or more of the activity relationships used in preparing the original network. For example, time can be saved by starting work on a particular activity, such as making arrangements for tendering to begin, before the completion of the activity upon which strictly it is dependent—in this case approval by the Department of Education and Science of the final plans.

A decision to take a risk of this kind must, of course, be based on an assessment of the likelihood that the work will have to be abandoned or modified. The question that must be asked is whether the amount of time that might be saved is worth the risk of possibly extending the total time if something were to go wrong. The magnitude of the risk involved can best be judged by management on the basis of their past experience. The actual effects of the decision on the total time needed to complete the project can be assessed with the help of the networks. These can be drawn to show the situation if the risk were successful, and if it failed. Only then need the final decision be taken.

Controlling the Project

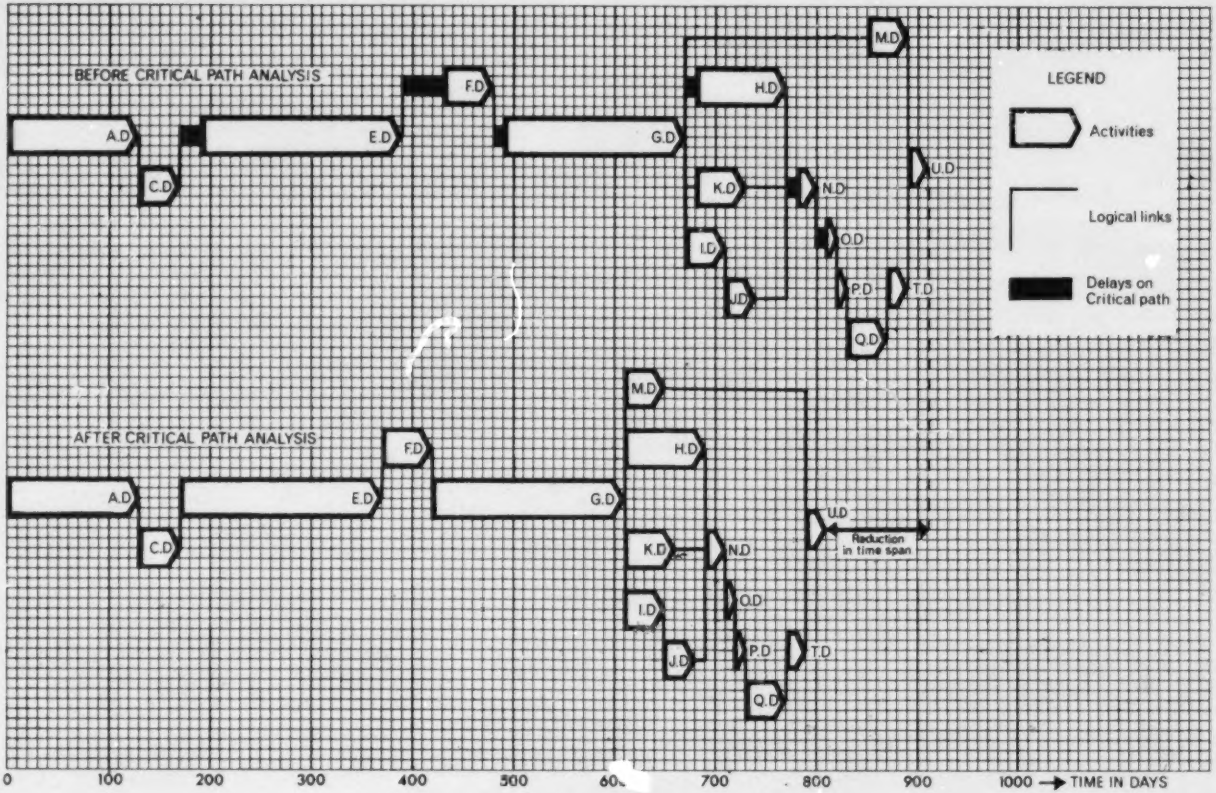
Before accepting the prepared network as a working schedule, it is necessary to confirm that the staff required to complete the project in the allotted time will in fact be available when they are needed. When this has been done the network is ready for use. It is, of course, helpful if one officer can be given overall responsibility for co-ordinating the project or projects that are in hand at any one time. Such adjustments as are necessary in relation to the project as a whole can then be made.

Close control can be kept over the progress of the project by the following means. A list can be compiled, one for each different activity in the network, of all the activities which can begin as soon as a particular task has been finished. The project controller can use these lists to initiate a new set of activities immediately following the completion of any job shown on the network. In this way unnecessary delays between activities can be avoided.

In Northumberland, it is estimated that a reduction of 10 per cent in the total time required to complete the projects in the 1964–65 Building Programme could have been achieved by scheduling the work as suggested here. The points at which time was saved varied considerably between different projects, depending on the allocation of resources in the original programme. The results achieved in one particular project, a primary school, are shown in Figure 3.

It is helpful if records of the duration of activities are taken. There are two reasons for this. The first is that the durations would be useful for guidance in preparing future networks. The second, and more important reason is that it would be possible by this means to see whether the work on the particular project is proceeding

Figure 3. The Effect of Critical Path Analysis on one School Building Project



according to schedule. If it is falling behind time it may be necessary to take corrective action so that no serious delays are carried through to the end of the project.

Occasionally an unforeseen activity will arise during the course of a project. When this happens it can be incorporated into the network and any necessary adjustments made. In this way the network provides an up-to-date picture of the work to be done to complete the project and allows a check to be made to ensure that the available resources are allocated in the most efficient and economic way.

Conclusions

The results of the analysis for Northumberland suggested that, on the basis of the 1964/65 programme, the time span of projects could be shortened by 10 per cent by using critical path methods to schedule the work.

Critical path analysis is in essence an exercise in logical thinking. It is also a means of making clear to all the participants in a complex enterprise the tasks they have to perform, the dates by which they should complete them, and the consequences on other participants if they fail to do so. Thus the existence of a network and its dissemination to all the participants can be a means of shortening the time required for the critical activities. There are two reasons for this: one, the psychological pressure of the deadline; the other, the knowledge of priorities which all concerned with the project have. If the time required for the critical activities can be shortened in this way, then time will be saved on the project as a whole.

The calculations involved in critical path analysis are simple arithmetic which can be easily carried out by clerical methods. Where the networks involved are large and complex, however—in particular those that require resources to be allocated economically between a number of concurrent projects—the use of a computer may be essential. A number of computer programs for this purpose are available.

The above report gives only a brief outline of how critical path analysis might be applied to administrative problems and some of the benefits that might result. A fuller description of the concepts and working of the method is included in each of the books listed below. The Unit will, of course, be pleased to give whatever advice and assistance may be required by member authorities who wish to enquire further about how critical path analysis might help in solving their administrative problems.

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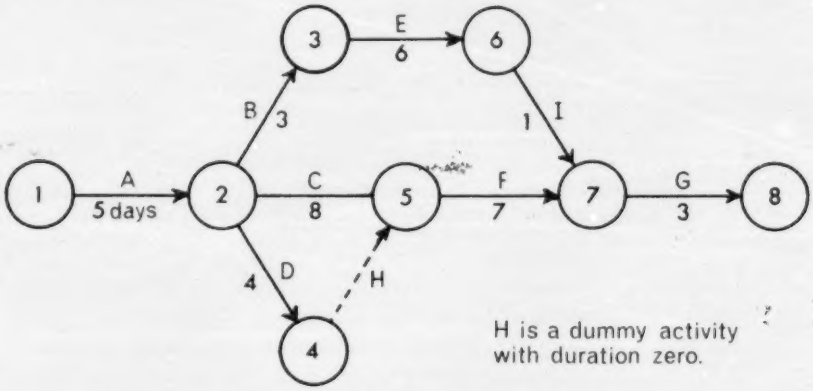
Calculation of Earliest and Latest Event Time

The arithmetic involved in calculating the earliest and latest event times is straightforward, but the process can sometimes be lengthy. When the network has been completed the length of time each activity is expected to take will have been entered, and the events numbered in sequence. An example of one such network is shown below.



The calculation of the earliest event times is carried out first. The earliest time of the first event in a network is conventionally set at zero. After this, the earliest event time for each subsequent event is calculated as follows. The earliest event time is given by adding the duration of the preceding activity to the earliest event time of the preceding event. Where there is more than one activity leading to the event, the earliest event time is taken as the maximum value obtained by the above process. In the diagram above, for example, the earliest event time for event 2, is the earliest event time for event 1, plus the duration of activity A. This is written as follows:

EET for event 1 = 0, by convention

EET for event 2 = EET(1) + duration (A) = 0 + 5 = 5

EET for event 3 = EET(2) + duration (A) = 5 + 3 = 8

EET for event 4 = EET(4) + duration (D) = 5 + 4 = 9

$$\text{EET for event 5} = \text{Max of} \begin{Bmatrix} \text{EET}(2) + \text{Duration (C)} \\ \text{EET}(4) + \text{Duration (H)} \end{Bmatrix} = \max \begin{Bmatrix} 5+8 \\ 9+0 \end{Bmatrix} = 13$$

EET for event 6 = EET(3) + duration (E) = 8 + 6 = 14

$$\text{EET for event 7} = \text{Max of} \begin{Bmatrix} \text{EET}(5) + \text{duration (F)} \\ \text{EET}(6) + \text{duration (I)} \end{Bmatrix} = \max \text{ of } \begin{Bmatrix} 13+7 \\ 14+1 \end{Bmatrix} = 20$$

EET for event 8 = EET(7) + duration (G) = 20 + 3 = 23

At this stage the earliest event time of the last event—which is also the date of completion of the project—will be known. The latest event time of the last event is taken as the earliest event time and the calculation of the latest event times carried out. The procedure is the reverse of that used to calculate the earliest event times:

LET for event 8 = EET(8), by definition = 23

LET for event 7 = LET(8) − duration (G) = 23 − 3 = 20

LET for event 6 = LET(7) − duration (I) = 20 − 1 = 19

LET for event 5 = LET(7) − duration (F) = 20 − 7 = 13

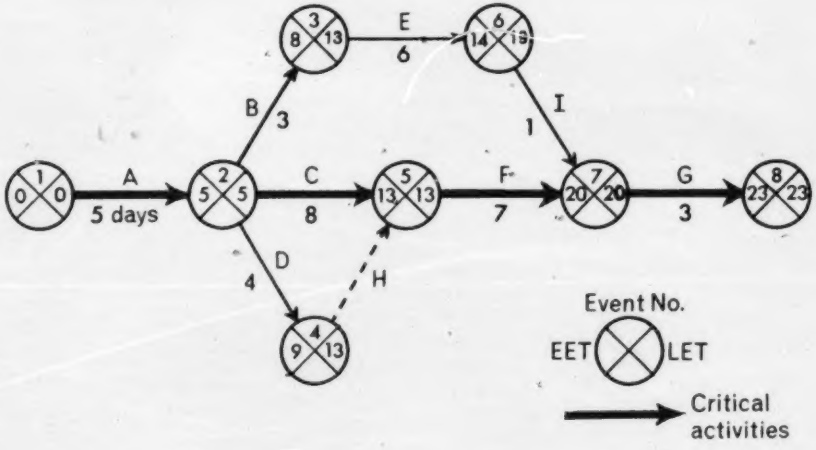
LET for event 4 = LET(5) − duration (H) = 13 − 0 = 13

LET for event 3 = LET(6) − duration (E) = 19 − 6 = 13

$$\text{LET for event 2} = \text{Min of} \begin{Bmatrix} \text{LET}(3) - \text{duration (B)} \\ \text{LET}(5) - \text{duration (C)} \\ \text{LET}(4) - \text{duration (D)} \end{Bmatrix} = \text{min of} \begin{Bmatrix} 13-3 \\ 13-8 \\ 13-4 \end{Bmatrix} = 5$$

LET for event 1 = LET(2) − duration (A) = 5 − 5 = 0

A simple check will ensure that the calculations have been carried out correctly, since the latest event time of the first event must, by definition, be zero. The completed network, on which both the earliest and latest event times have been entered, is shown below.



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Swansea
Teesside
Wallasey
Warrington
West Bromwich
Wigan
Wolverhampton

County Boroughs (Scotland and Northern Ireland)
Belfast
Glasgow

County Councils (England and Wales)
Bedfordshire
Berkshire
Buckinghamshire
Cambridgeshire and Isle of Ely
Carmarthen
Cheshire
Cornwall
Denbighshire
Derbyshire
Dorset
Durham
Essex
Flintshire
Glamorgan
Gloucestershire
Hampshire
Hertfordshire
Huntingdon and Peterborough
Isle of Wight
Kent
Leicestershire
Lincs. (Kesteven)
Lincs. (Lindsey)
Merioneth
Monmouthshire
Northumberland
Nottinghamshire
Oxfordshire
Pembrokeshire
Somerset
Suffolk (East)
Surrey
Sussex (East)
Warwickshire
Wiltshire
Worcestershire
Yorks. (E. Riding)
Yorks. (W. Riding)

County Councils (Scotland)
Aberdeen
Dunbarton
Fife
Lanark
Midlothian
Renfrew
Stirling
West Lothian

States of Jersey

The services of the Unit are also available to those county districts in the areas of member county councils which have populations of 30,000 or more or which employ work study officers.